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FINAL REPORT

"THE PHYSICS AND CHEMISTRY OF DUSTY PLASMAS:  
A LABORATORY AND THEORETICAL INVESTIGATION"

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## FINAL REPORT ON NASA GRANT NAGW-399

This final report summarizes briefly the research that has been carried out on NASA Grant NAGW-399, entitled "The Physics and Chemistry of Dusty Plasmas: A Laboratory and Theoretical Investigation". The work was performed under the auspices of the University of California at San Diego. The principal investigator was Dr. Elden C. Whipple.

The work is summarized under the two headings of:

1. Theoretical Investigations, and 2. Laboratory Investigations. Copies of abstracts of all publications resulting from this work are enclosed as well as copies of two UCSD reports: one entitled, "Progress Reports on Laboratory Investigations of Dusty Plasmas", and the other entitled, "A White Paper on Dusty Plasmas".

The latter report, "A White Paper on Dusty Plasmas" was prepared as a summary of a workshop held at the end of the grant period, on February 10-11, 1986, at the University of California at San Diego. The purpose of the workshop was to review the work on dusty plasmas that has been accomplished, and to make recommendations for further research. The availability of the White Paper was made known to the scientific community by means of a "Meeting Report" published in Eos (Vol. 67, pg. 658, Sept. 1, 1986). A number of copies of the White Paper have been distributed in response to requests from interested scientists.

### 1. Theoretical Investigations

Theoretical work on dusty plasmas has been in three areas: collective effects in a dusty plasma, the role of dusty plasmas in cometary atmospheres, and the role of dusty plasmas in planetary magnetospheres-- particularly in the ring systems of the giant planets.

#### (1) Collective effects

In a plasma/dust mixture, the average charge on a grain can be quite different than the charge on an isolated grain in a plasma when the intergrain distance is on the order of or smaller than the plasma Debye length. In the latter case the dust particles electrostatically screen each other and the average charge is significantly less than for an isolated grain. There can still be overall charge neutrality but there is now a significant space charge in the plasma that balances the charge on the grains. In effect, the whole intergrain plasma becomes a plasma sheath.

The electrostatics of a dust/plasma system was analyzed using three different models: a permeable grain model (where it is assumed that the plasma can penetrate the grains), an impermeable grain model, and a capacitor model. The results of the three models are similar but

not identical. The charge on a grain and the grain to plasma potential are determined primarily by a parameter  $Z = 4 \pi \lambda^2 C$ , where  $\lambda$  is the Debye length,  $N$  is the dust concentration, and  $C$  is the capacitance of the grains (where all the grains are the same size). This parameter is the approximate ratio of the charge per unit volume expected on isolated grains to the available charge per unit volume in the plasma. When  $Z$  is larger than unity, then depletion of the plasma occurs and the charge on the grains is significantly reduced. This work was published in the Journal of Geophysical Research (Whipple et al, 1985).

This work has been extended to include the effects of a dust size distribution. The results of the analysis are qualitatively similar to what was obtained for grains of a single size in a plasma. The depletion of electrons and the limiting of the charge on the dust grains depends on the same parameter  $Z = 4 \pi \lambda^2 N \bar{C}$  where now  $\bar{C}$  is the average capacitance of the dust grains in the plasma. This work has been reported on at the 1985 Fall AGU meeting (Houpis, 1985), and a paper describing the results is in preparation.

## (2) Cometary Atmospheres

Electromagnetic forces play an important role in the dynamics of smaller cometary dust grains because of the fact that the grains are immersed in a plasma and radiative environment and are therefore charged to some electrostatic potential. These charged grains experience forces from magnetic fields and convectional electric fields in both the undisturbed solar wind and in the region of the shocked solar wind outside a cometary ionopause.

The charge on a dust grain is determined by a balance between various charging currents: the most important are photoemission, the current caused by impact of plasma electrons and ions, and secondary emission of electrons caused by electron impact. The charging times are relatively long for small dust grains with the result that for dust grains in some environments a time-dependent calculation of the grain charge must be performed in order to follow its orbit accurately.

A simple model of the particles and fields around a comet was used to calculate the trajectories of the smallest (micron and submicron sized) dust grains that were expected to be released from a cometary nucleus (Horanyi and Mendis, 1985). It was shown that electromagnetic forces associated with the motion of the grains through the magnetized plasma played a crucial role in their dynamics. The calculations showed the existence of asymmetrical envelopes of the sunward dust clouds and also the possible existence of wavy dust features far down the comet tail, similar to the wavy dust feature observed in the dust tail of Comet Ikeya-Seki 1965f.

This work was extended by taking into account the motion of the comet around the sun, since this effect is important for dust trajectory times of more than a few days, and the calculations were applied to the

motion of dust grains in the tail of Comet Giacobini-Zinner (Horanyi and Mendis, 1986a). It was found that the distribution of the grains--particularly at the lowest end of the mass spectrum--in a plane normal to the orbital plane is entirely different from what had been expected for uncharged grains. The recent in-situ observations from the ICE spacecraft of the distribution of fine dust in the environment of Comet Giacobini-Zinner were consistent with the calculations.

Similar calculations were performed for Comet Halley (Flammer, Jackson, and Mendis, 1986; Horanyi and Mendis, 1986b). In the first of these papers, the authors show that observed sporadic variations of the brightness of Comet Halley at large heliocentric distances (8-11 AU) are closely correlated with the encounter of high-speed solar wind streams. They proposed that during such periods the night side of the comet is electrically charged to numerically large negative potentials, with consequent electrostatic levitation and blow-off of fine charged dust grains lying on the surface of the cometary nucleus. In the second paper the authors simulated the fine dust distributions near Halley's comet during both its 1910 and its 1986 appearances. The dust cloud morphology as seen from earth in 1910 corresponded to larger grains, where the effect of the electrical forces was too small to be clearly observed. For the 1986 flybys of the comet by the various cometary spacecraft it was found that the distribution of the lower end of the dust mass spectrum was largely determined by the direction of the interplanetary magnetic field. The dust detectors on the Vega spacecraft detected the smallest grains much farther away from the comet than expected, well outside their bounding paraboloids defined by classical theory based on radiation pressure deceleration. These observations are consistent with the numerical calculations.

### (3) Planetary Magnetospheres

The stimulus for a great deal of the research on the physics of dusty plasmas has come from the observations of the ring systems of the planets, and particularly the observations of the fine structure in Saturn's rings. One of the early activities under this grant was the participation in the writing of two reviews: one, "Dust-Magnetosphere Interactions" (Grun, Morfill and Mendis, 1984) appeared as a chapter in the Book "Planetary Rings" (eds. R. Greenberg and A. Brahic), and the other on electrodynamic processes in the Saturnian ring system (Mendis et al, 1984) appeared as a chapter in the book "Saturn" (ed. T. Gehrels). The various interactions between magnetospheric particles, fields and dust grains, and pertinent observations were reviewed in these articles. Energetic particle absorption signatures reveal information about the mass concentrations of particulates in Jupiter's and Saturn's magnetospheres. The drift of dust particles induced by systematic and stochastic charge variation and by the plasma drag was described. Sputtering and mutual collisions affect the sizes of grains. Electromagnetic effects were discussed which lead to the halo of Jupiter's ring, the dust distribution in Saturn's E-ring, and to levitated dust in the B-ring spokes as well as on the moon.

Plasma effects on the dust grains in Saturn's ring system were discussed by Houppis and Mendis (1983) who pointed out that a dust disc in a planetary magnetosphere constitutes a dust-ring current which is subject to the finite-resistivity tearing mode instability. They suggested that the observed fine ringlet structure of Saturn's rings might be a relic of this process operating in the past. Mendis, Hill and Houppis (1983) and also Mendis et al (1984) brought together several aspects of electrodynamic interactions in a discussion of the formation and evolution of the B-ring spokes, the formation of F-ring waves, eccentricities in certain isolated ringlets, and the origin and morphology of the broad diffuse E-ring. Ip and Mendis (1983) looked at the consequence of the ring current in Saturn's D-ring driving field-aligned currents near the dawn and dusk terminators and closing through the Saturnian ionosphere. They suggested that depletion of the content of Saturn's ionosphere might be caused by this effect. Finally, Northrop et al (1986) suggested that the newly discovered "gossamer" ring of Jupiter, composed largely of micron-sized grains and existing in a very narrow band near synchronous radius, is probably the result of a "gyrophase" drift towards synchronous orbit of very fine, charged grains.

## 2. Laboratory Investigations

### (1) Studies of Dust/Plasma Interactions

Hy-Tech Research Corporation, under sub-contract to UCSD, has developed an experimental system to study the interaction of small (0.01 to 1 micron diameter) particles with a background plasma. A complete description of the experimental system and of the results that have been obtained is given in the enclosed report entitled, "Progress Report on An Experimental Investigation of Dusty Plasmas". A paper describing this system and experimental results is being prepared for publication.

In the experiment, a beam of dust particles is generated and injected into a plasma and the interactions of the dust particles with the plasma are measured. To produce the particles, a refractory metal is evaporated in a vacuum oven and nucleated in a cooled chamber. Bismuth has been used in the experiment because of its low melting point. By differentially pumping the dust cloud through a series of orifices, a beam of dust particles (up to several thousand per  $\text{cm}^3$ ) is produced which can then be directed through a plasma where the electron densities range from  $10^7$  to  $10^9$  per  $\text{cm}^3$ , and where the electron temperature is on the order of a few eV.

The charge distribution on the grains in the plasma is determined by measuring the current carried by the grains as a function of retarding voltage when they impact the collecting electrode of a retarding potential analyzer. In the case when the grains have come to an equilibrium potential with the plasma before impacting the collector, the shape of this current/voltage curve gives directly (after differentiation) the particle size distribution. The size distribution

determined in this fashion agrees very well with size distributions derived from electron micrographs of collected dust particles on a glass slide.

An important aspect in the evolution of dust grains in space is the collisional processes that occur, including elastic collisions, inelastic collisions which change internal energies, sticking collisions, and disruptive collisions. Such processes have never been studied before for microscopic grains in the velocity range that is available here--on the order of tens of meters/sec. It is important to understand how these collision processes can be affected by the charge on the grains.

After determining that the charging process of the grains in the plasma was well understood, the experimental system was modified so that two dust beams could be produced and simultaneously injected into the plasma in intersecting trajectories. The intent here was to obtain grain/grain collisions so that collision processes could be studied. A diagnostic scheme involving Rayleigh scattering of light from the grains using a 5 mW Helium/Neon laser was used to determine the dust beam density profile and the precise locations of the beams. It was estimated that about 1 collision per sec between grains could be expected in the intersection volume between the two beams (with grain concentrations of  $5000 \text{ cm}^{-3}$ , a grain radius of .05 microns, and beam velocities of 50 m/sec with the two beams at right angles).

In order to obtain information about the collision processes it was necessary to detect and measure the properties of the individual collision products. At the end of the grant period, two schemes were being developed: an improved laser scattering technique that could detect the individual collision products in flight; and an electron multiplier detection system which would detect the collision product on impact through the secondary electrons it would produce. Initial measurements indicated that the collision products were being detected, but further work was required to optimize and characterize the system and to measure particle collision rates.

## (2) Stimulated Molecular Excitation and Infrared Emission by Charged Dust Grains

Charged dust grains can have a large electric field at their surface because of their small size. If a molecule passes in the near vicinity of such a grain this electric field can change the rotational energy of the molecule. Once the molecule is in an excited rotational state, it might be possible for rotation-vibration coupling to distribute the energy into vibrational motion. This energy when released would be emitted in the infrared region of the spectrum, and it is possible that some of the unidentified infrared emissions observed in a wide range of astrophysical objects might be a result of this excitation mechanism.

An experiment was designed and built at UCSD to test the efficiency of this mechanism. In the experiment, the charged grains

were simulated by thin wires in a metallic brush. The wires, while larger in diameter than the interstellar grains, were charged to a correspondingly higher potential in order to keep the magnitude of the electric field at their tips comparable to the expected fields at the surfaces of the dust grains. The experiment was designed to be carried out at either cryogenic or room temperature in order to determine the effects of molecules frozen on the grain surface. Since it had been proposed that the unidentified infrared emission lines might correspond to stretching and bending modes of the various bonds of carbon and hydrogen atoms, hydrocarbons with dipole moments were primarily used as test gases. A spectrometer covering the spectral range from 1 to 14 microns was used to look for infrared emissions.

The experiment was not successful in detecting infrared emissions that could be unambiguously ascribed to the proposed excitation mechanism. Preliminary spectra were obtained which had some suggestive features at some of the wavelengths appropriate to the astronomical unidentified infrared emissions. However, there were still difficulties with background subtraction and with instrument stability which prevented conclusive results from being obtained before the end of the grant period.

### 3. Publications

Flammar, K. R., B. Jackson and D. A. Mendis, "On the Brightness Variations of Halley's Comet at Large Heliocentric Distances", Earth, Moon, and Planets, 35, 203, 1986.

Grun, E., G. E. Morfill and D. A. Mendis, "Dust-Magnetosphere Interactions, in Planetary Rings (Eds. R. Greenberg and A. Brahic), University of Arizona Press, p. 275, 1984.

Horanyi, M., and D. A. Mendis, "Trajectories of Charged Dust Grains in the Cometary Environment", The Astrophysical Journal, 294, 357, 1985.

Horanyi, M., and D. A. Mendis, "The Dynamics of Charged Dust in the Tail of Comet Giacobini-Zinner", J. Geophys. Res., 91, 355, 1986a.

Horanyi, M., and D. A. Mendis, "The Effects of Electrostatic Charging on the Dust Distribution at Halley's Comet", The Astrophysical Journal, 307, 800, 1986b.

Houpis, H. L. F., and D. A. Mendis, "The Fine Structure of the Saturnian Ring System", The Moon and the Planets, 29, 39, 1983.

Houpis, H. L. F., "Electrostatic Charge on a Dust Size Distribution in a Plasma", EOS, 66, 948, 1985, (Abstract).

Ip, W.-H., and D. A. Mendis, "On the Equatorial Transport of Saturn's Ionosphere as Driven by a Dust-Ring Current System", Geophys. Res. Lett., 10, 207, 1983.

Mendis, D. A., J. R. Hill and H. L. F. Houpis, "Charged Dust in Saturn's Magnetosphere", J. Geophys. Res., 88, 929, 1983.

Mendis, D. A., J. R. Hill, W.-H. Ip, C. K. Geortz and E. Grun, "Electrodynamic Processes in the Ring System of Saturn", in Saturn (Eds. T. Gehrels and M. S. Matthews), Univ. of Ariz. Press., p. 546, 1984.

Mendis, D.A., J. R. Hill, W. Fillius, and T. G. Northrop, "A Note on Jupiter's Gossamer Ring", submitted to Nature, 1986.

Whipple, E. C., T. G. Northrop and D. A. Mendis, "The Electrostatics of a Dusty Plasma", J. Geophys. Res., 90, 7405, 1985.

Whipple, E. C., "A White Paper on Dusty Plasmas", UCSD Report, April, 1986.

Yadlowsky, E. J., and R. C. Hazelton, "Progress Reports on an Experimental Investigation of Dusty Plasmas", UCSD and Hy-Tech Research Corporation Report, 1986.